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# DIAMOND-SHAPED SEMICONDUCTOR RING LASERS FOR ANALOG TO DIGITAL PHOTONIC CONVERTERS

**Binoptics Corporation**

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Photonic/optoelectronic analog to digital converters (ADCs) have advantages in areas such as precise sampling times, narrow sampling apertures, and the ability to sample without contaminating the incident signal. They also have potential to offer the highest sampling rates and bandwidths. Significant challenges remain in the development of photonic ADC architectures and associated components (e.g. compactness, reduce power consumption v. efficiency, improved mechanical and thermal stability, etc.). Monolithically integrated photonic solutions may be the best avenue to address these issues. The bi-directional ring laser is a promising approach to achieving the basic combinational digital photonic logic functions. This study investigated the switching capabilities of diamond shaped ring lasers. Future expectation is that these devices can be used as accurate comparators for optical signals at speeds of 10GHz and above. Switching has been shown with injected powers of less than 2µW and speeds of 10GB/s. Extinction ratios are in the region of 10dB. The comparators can be used as either optical amplitude comparators or wavelength comparators, due to the 0.5L wavelength working range of the devices. It is believed that with further technical investigation and development, these devices will be an aid in fast optical ADC and switching applications.

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## Summary

This study has investigated the switching capabilities of diamond shaped ring lasers and has delivered 7 lasers to AFRL (ROME). The future expectation is that these devices can be used as accurate comparators for optical signals at speeds of 10GHz and above.

Switching has been shown with injected powers of less than 2μW and speeds of 10GB/s. Extinction ratios are in the region of 10dB.

Wavelength and polarization control are critical. The strength of etched facet technology for monolithic integration will aid the complexity of polarization and wavelength control, and allow for many devices to be put together in an array, or cascaded. Other components such as optical amplifiers, mirrors and photodiodes can be integrated. This has been demonstrated previously by BinOptics.

The comparators can be used as either optical amplitude comparators or wavelength comparators, due to the 0.5Å wavelength working range of the devices.

It is believed that with further technical investigation and development, these devices will be an aid in fast optical ADC and switching applications.

## Introduction

This report is the result of the work carried out for Air Force Research Laboratory, Rome (AFRL) in response to BAA-01-05-IFKPA. This study shows the initial testing of diamond shape ring lasers for possible application in optical analog to digital converters (ADCs).

Ring lasers have two circulating modes traveling clockwise (CW) and counterclockwise (CCW). These two directional modes, in this current design, exit the laser at different angles from the same facet. The angular separation is 86°, shown in Figure 1, and thus offers easy discrimination between outputs. The ability to switch between these modes by optical injection has been shown to allow the ring laser to be used as an optical signal inverter, and be scaled to multiple input logic gates.[1] The intention here is to investigate these devices as fast comparators for use in ADCs. In addition to the switching, these devices also have great potential for use in ADC and fast switching applications, as they are scaleable and monolithically integrable with optical amplifiers, photodiodes, electroabsorption (EA) modulators etc.

The purpose of this work is to investigate the power required to switch the laser and the speed at which the switching can be achieved.

## Experimental Technique

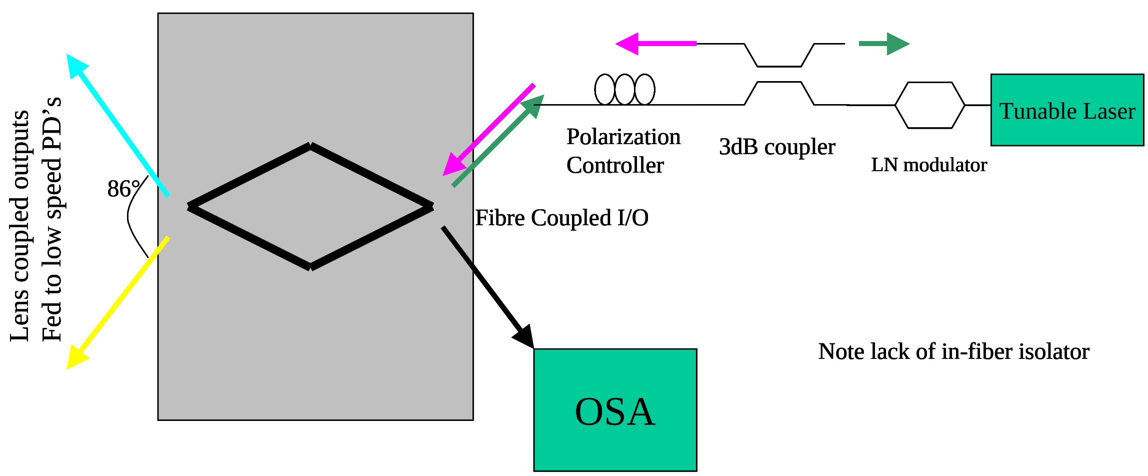


**Figure 1. Schematic of measurement apparatus.**

The operation of the ring laser depends on having two independent modes traveling in opposite directions. If light is coupled from one mode to the other then their independent nature can be compromised. Some coupling, however, will result from scatter at facets and from defects within the device. Care, therefore, has to be taken to prevent unwanted reflections in the measurement apparatus entering the laser. To achieve this, anti-reflection coated optics and lensed fibers have been used.

The experimental set-up is seen in Figure 1. A 3dB coupler is used to monitor both the input injected pulse (pink) and the output from the laser (green), which is from the mode in the opposite direction of the injected pulse. This setup does not allow an isolator to be used in the injection path, thus some reflection may get back to the laser.
Other outputs from the ring device go to an optical spectrum analyzer (OSA), to monitor the spectrum, and to low bandwidth photodiodes.

The injected pulses are generated from a Lithium Niobate (LN) modulator capable of operation beyond 10GHz. There is some noise and ripple generated by the driver used for the LN modulator, which may result in small optical pulses when no light should be present. Careful biasing of the modulator and reduced bias on the FET amplifier help to reduce this.

The optical injection has to be matched to the light of the lasing mode. This has to be done both in wavelength and polarization. This is critical and will be demonstrated. The wavelength of both injected light and the lasing of the ring can be seen on the OSA when they are separated by 0.5nm or more, but the alignment of the wavelengths has to be greater than the resolution of the available OSA.

The lasers used in this study have a 600μm round trip cavity length, and are injected with 120-175mA of current. Lasing threshold is 75mA for these devices. The laser is mounted on a temperature controlled copper pin and maintained at 20°C.

## Results and Discussion

The broad spectrum of the ring laser device can be seen in Figure 2. These devices have a similar spectrum to a Fabry-Perot laser, but can at times offer a single wavelength peak sometimes 30dB stronger than its neighbors. Injection of the optical switching signal was made at the peak wavelength, but results from injecting into neighboring peaks show similar results. Figure 3 shows the spectrum in greater detail with and without injection. The injected light preferentially excites one cavity mode, and as shown, makes it 40dB above the other modes. This is an efficient way of knowing that the injection is at the correct wavelength and polarization.

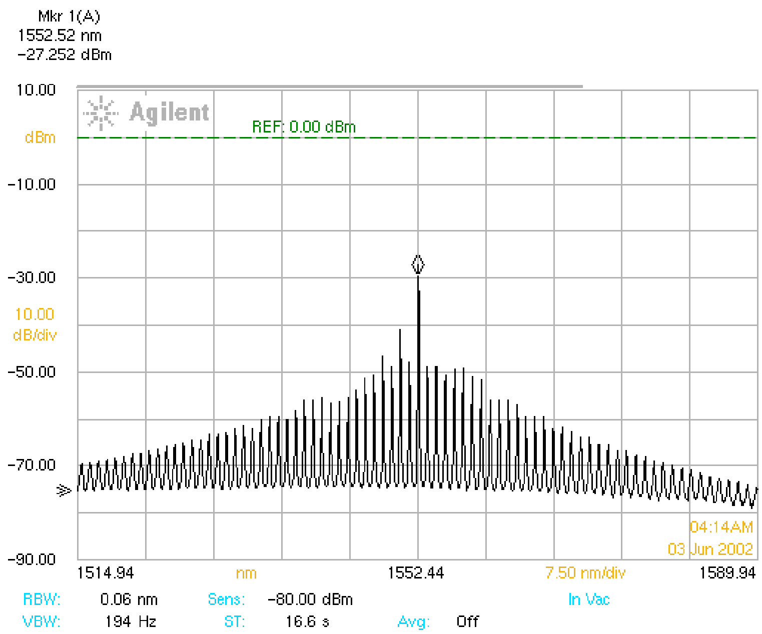


**Figure 2. Spectrum of ring laser.**

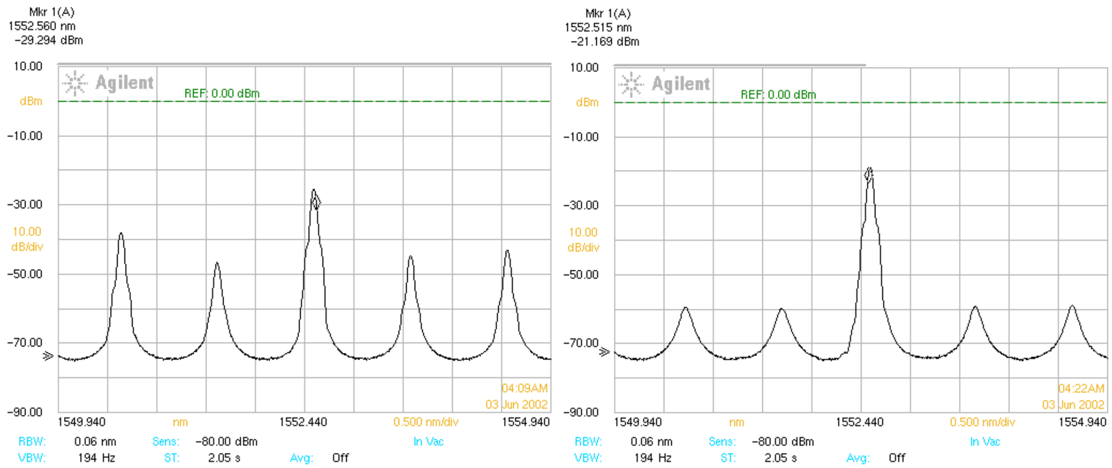


**Figure 3. Spectra of ring laser without and with injection of light.**

## Power Sensitivity

To investigate the power level required to switch the ring laser, a slow ramp was fed into the LN modulator to give a slowly increasing optical injection. The speed was kept low (100Hz) to remove any restriction of the results from the low bandwidth of the detectors. Figure 4 shows the resulting traces from the oscilloscope. The trace colors match with the arrows in Figure 1. The fiber coupled return signal (green) shows a maximum extinction ratio of 7-10dB. The large area detectors show a lower value, but are not as precisely coupled.

Taking the data from Figure 4 and plotting the injected light against the output light in the CCW mode a figure for the power required to induce switching can be obtained. This result is shown in Figure 5 for different wavelengths.
It can be seen from these results that the device is not truly bi-stable but has an exponential response to injected light. (the experiment was done at slow speed to ensure that the exponential decay is due to light level and not response time of the photodiodes (PD's)). This is possibly due to reflections coupling the two modes of the laser, either from the fiber setup, or from within the laser.

The other noteworthy point is that the device is sensitive to wavelength. Figure 6 shows the injected light power required to reduce the output by 50%. It can be seen that at the optimum wavelength, the power required can be as low as 7µW. This data is the power in the lensed fiber presented to the laser. Calibrating out the coupling of the fiber to the laser, it is estimated that the power needed is 5 times lower, i.e. 1.5µW.

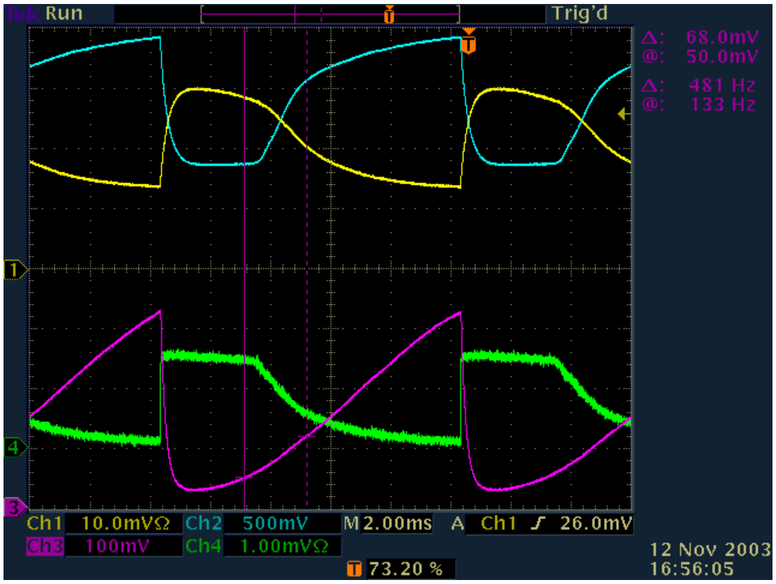


**Figure 4. Oscilloscope traces resulting from a slowly ramped injection. Trace colors match the arrows in Figure 1.**

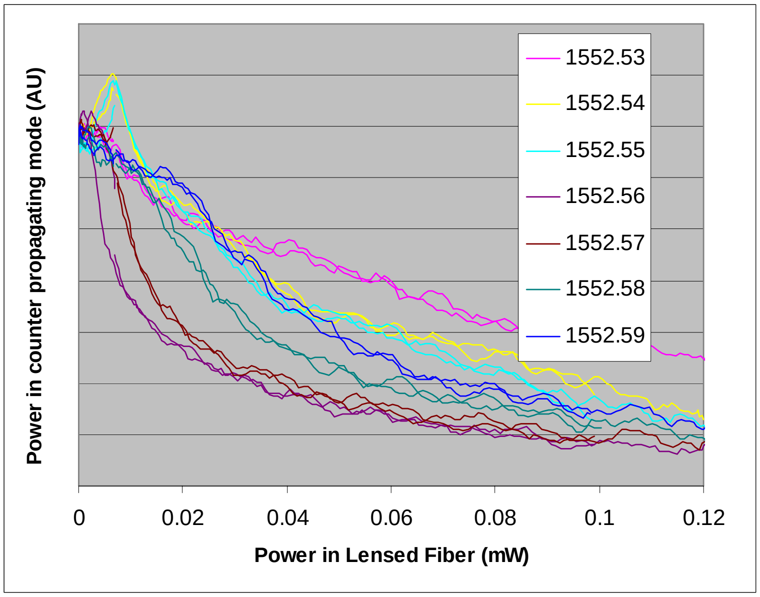


**Figure 5. Power in CCW mode as a result of injection in CW mode.**

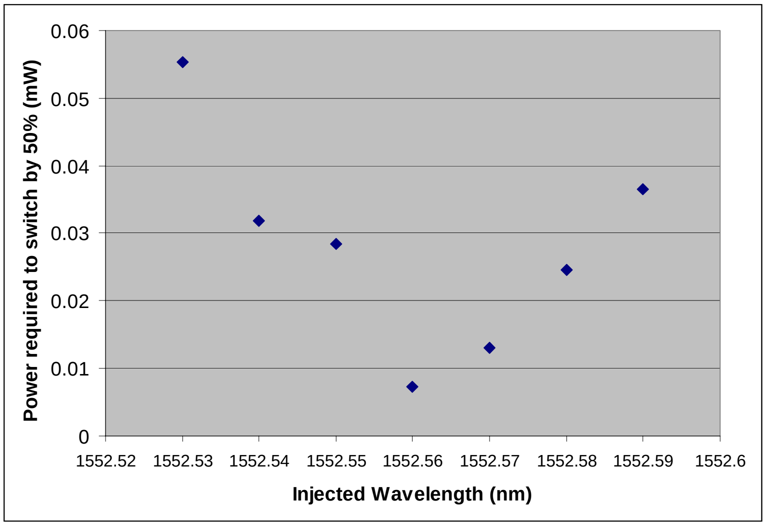


**Figure 6. Injected power required to switch as a function of wavelength.**

## Speed Sensitivity

To investigate the speed at which these devices could operate, a digital ‘1’ was sent to the LN modulator from a data generator operating at 1Gb/s, 5GB/s and 10GB/s, giving pulses of 1000, 200 and 100ps respectively. The injected power was in the region of 100µW during the pulse. The responsivity of the high-speed detector is smaller than the lower bandwidth (BW) devices, thus a higher power level was used to see the signal clearly.

The results below are measured on a Tektronix TDS8000 digital oscilloscope. The relative timing of the injected pulse and the response will not be accurate, as the lengths of fiber used during the measurement will give a different time delay to the two signals. This effect becomes more noticeable at higher speeds.

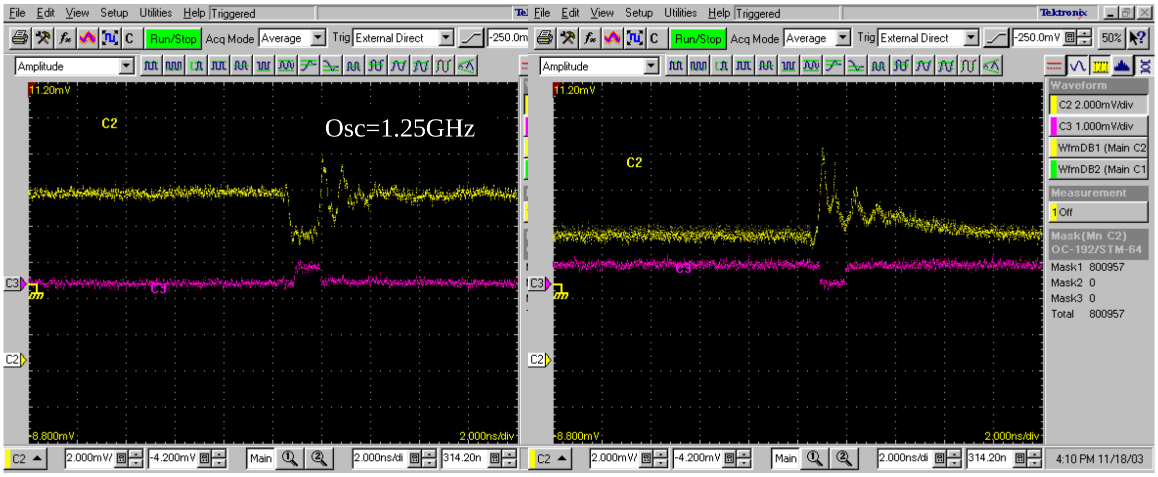


**Figure 7. Output from CCW mode (yellow) resulting from 1000ps injected pulse (pink).**

Figure 7 shows the inverted output from the ring laser in the two cases of a positive pulse and a negative pulse both 1000ps in length. Switching is clear, but at an extinction of approximately 3dB, and showing some ringing in the response. The ringing frequency here is at 1.25GHz, but a small change in input can affect this speed. Figure 8 shows a double pulse giving a ringing frequency of 3.6GHz. Given that wavelength and injection current to the laser remained the same, the variables are a small polarization change or, more likely, residual reflections from the apparatus which will give reflections at different times due to the double pulse.

Figure 9 shows the inverted and non-inverted response from a 200ps pulse. Switching is again achieved, with oscillations of different frequencies. The 6-8GHz oscillations are the relaxation oscillations of the laser and indicate the region of the upper speed limit of this particular device. The slower oscillation is likely to be from system reflections. It is also interesting to note that the inverted output transforms a positive 200ps pulse into a 500ps pulse, but takes about 2500ps to recover from a negative going pulse. The non-inverting output shows a faster rise times, but still the negative going pulse has the slower response.

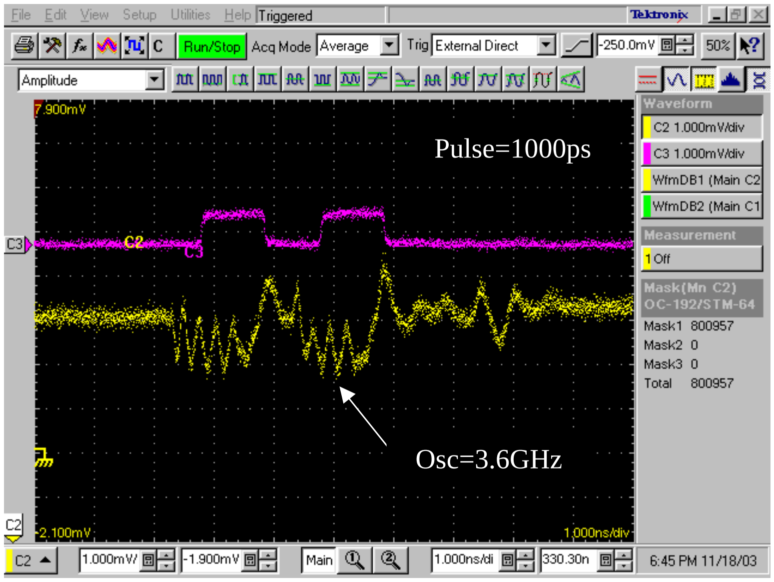


**Figure 8. 1000ps injected pulse giving oscillating output.**

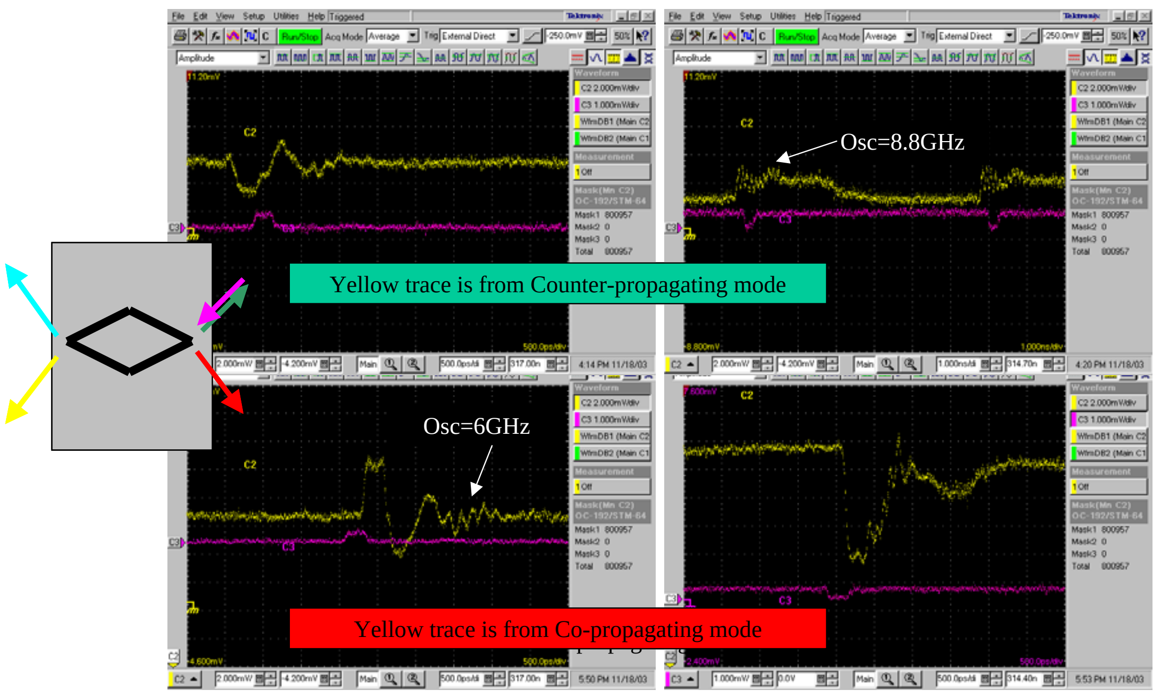


**Figure 9. Results from 200ps pulse. (Care! timescales vary)**

Going to a 100ps (12.5Gb/s) pulse the laser still switches, but shows the same oscillations and recovery time that was seen with 200ps pulses. Figure 10 shows the traces from the

100ps pulse experiment.  The co-propagating trace (bottom right) shows the injected pulse is reproduced very well in the output, showing that a high speed operation is possible.  Further oscillations later in the trace may be due to the device or stray reflections from the measurement system.

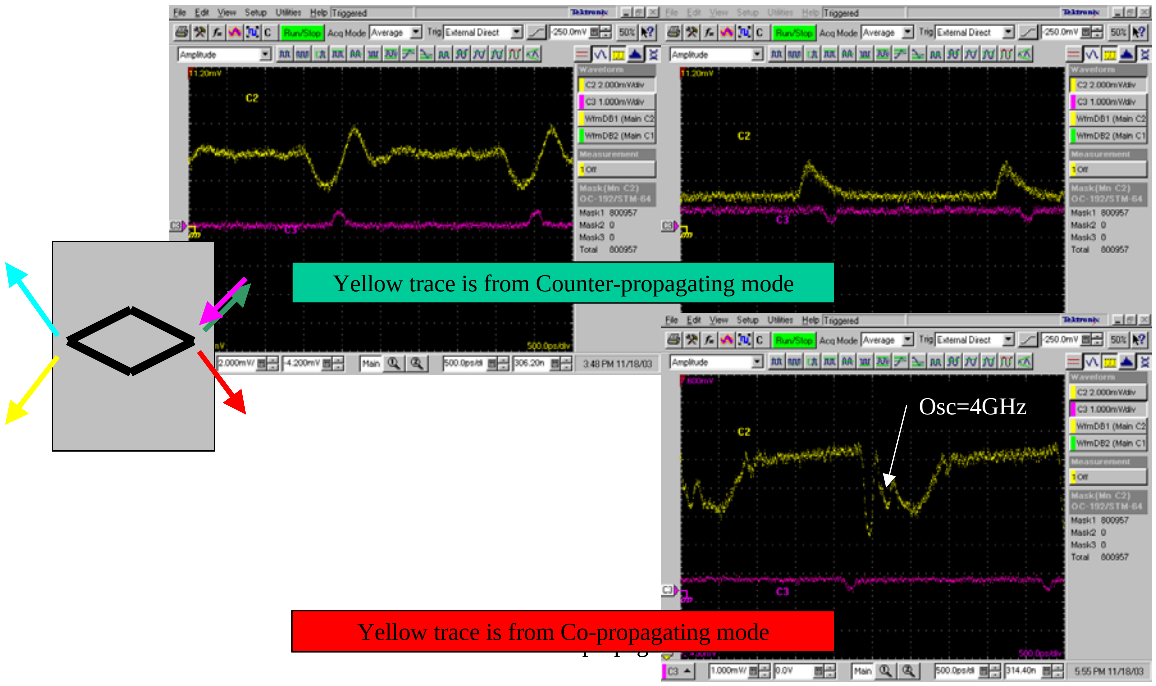


**Figure 10.  Results from 100ps pulse.**

In order to resolve the source of the oscillations, a reduced experimental setup was used where only the lensed fibers were used and isolators were implemented where possible

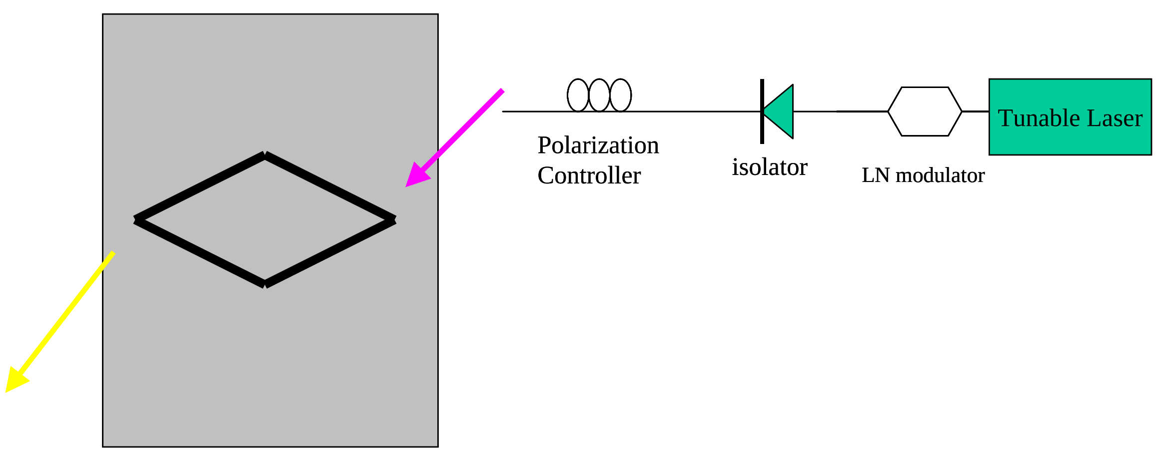


**Figure 11.  Reduced set-up.**
**Only lensed fibers used, with greater distance between fiber and laser to reduce reflection.**

With the reduced reflections some slight improvement is seen in the response.  Figure 12 shows a 100ps pulse (10GB/s bit) and the inverted response similar to that in Figure 10. The oscillations are similar but cleaner and the inverting signal is broadened.

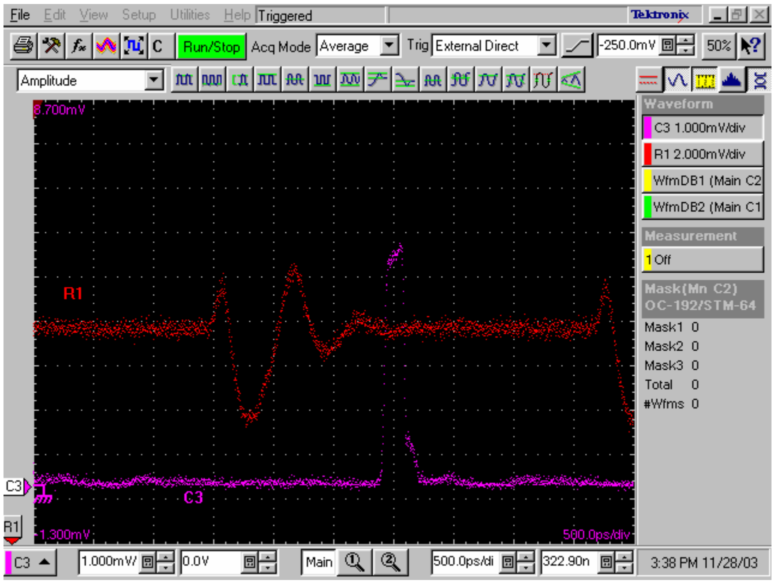


**Figure 12.  10gb/s pulse with reduced reflections.**
**Purple is injected pulse.  Red is output from inverting mode.**

To ascertain the source of the oscillations, the current into the laser was increased to 175mA. The injected wavelength has to be adjusted to account for the shift in spectrum from heating.   Figure 13 compares the laser response at 135mA and 175mA, and clearly shows that the higher current has higher frequency oscillations as expected if they are due to the laser relaxation frequency alone.  With the reflections in the fibers removed, this is the only oscillation left.

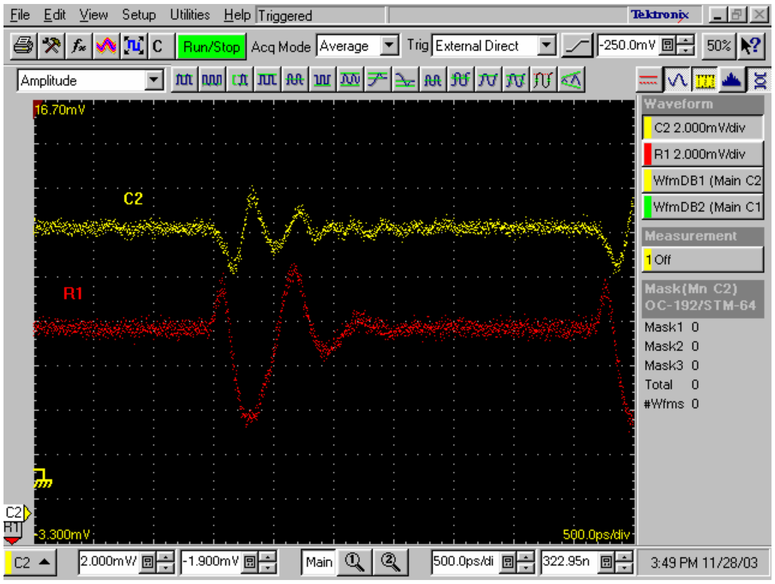


**Figure 13. 10Gb/s pulse at 135mA (red) and 175mA (yellow).**

Figure 14 shows the laser response to the negative going pulse. With careful adjustment a relatively clean and narrow pulse can be seen from the device. The slow response after the pulse seen in Figure 10 is not present here, leaving an inverted pulse that matches the input pulse even in the shoulder on the trailing edge.

To arrive at this cleaner pulse, careful adjustment of polarization, wavelength and input pulse characteristics have to be made. The extra distance of the lensed fiber from the laser will also have reduced the injected optical power, which may give less perturbation to the carrier density of the laser.

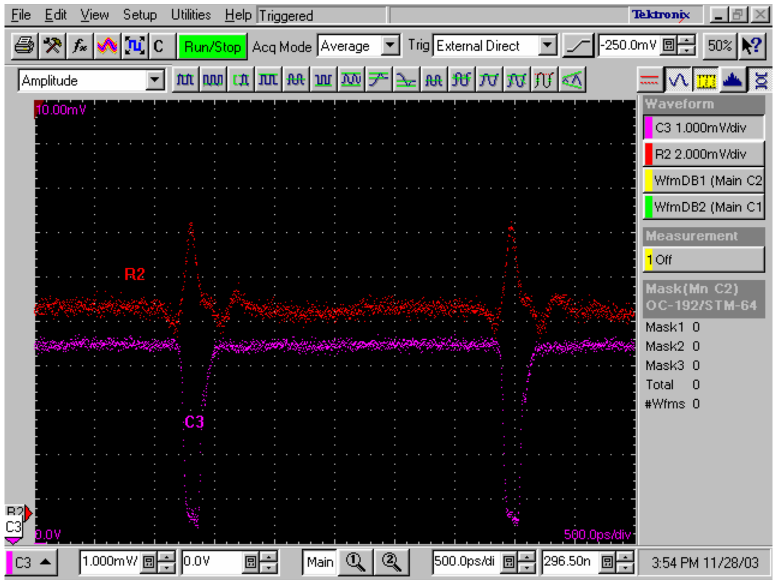


**Figure 14. 10Gb/s pulse at 175mA with reduced oscillation.**
**Purple is injected pulse, Red is inverting output.**

## Future Possibilities

It has been shown here that the bi-directional semiconductor ring laser can invert signals at a speed of 10Gb/s, with very little optical injection. Great care has to be taken in matching wavelength, polarization, and injected pulse shape. These latter items become easier to control if the devices are monolithically integrated with other sources, which is easy to achieve with etched facet technology. The control of facet positions will also allow reduced reflections, as facet angle does not have to be perpendicular to the cavity. Monolithic integration of other structures such as SOA and fast PD devices is also possible.

Speed is a key issue here, and the interference of relaxation oscillations has brought doubt into the suitability of these devices. However, it has been shown that increasing current will increase relaxation frequency, and a shorter cavity will do the same. Linear lasers have been made by BinOptics with relaxation frequencies above 15GHz. Much higher frequencies are possible. The injection of light will also increase the resonant frequency, but at the injection levels here, this should be a minimal change.

This assumes that the switching is done by influencing the carrier density. Ideally, the switching would be achieved by preferentially exciting one mode or the other by injection, and keeping the carrier and photon densities the same. This process would be much faster than the carrier related effects.

The next requirement on the way to building an optical ADC would be to fabricate more devices and characterize the ability to act as an accurate comparator. The devices measured in this work showed the ability to switch, but extinction ratio is a function of injected power

## Conclusions

It has been shown that diamond shaped semiconductor ring lasers can be switched with very small injected powers in the region of 2µW.

Wavelength sensitivity has also been shown to be important. The range of wavelengths that will show switching is limited to 0.5Å. These devices can, therefore, be used as amplitude or wavelength comparators.

The speed of the laser devices is limited, in this work, to the relaxation frequency of the laser. In this case, 4-8GHz has been seen, but devices with 15GHz oscillations have been made by this company, and 20GHz and above can be made. If the switching can be made independent of the carrier density, then much greater speeds could be achieved.

The measurement of these devices is very complex, with accurate control of wavelength and polarization, whilst minimizing reflections. The strength of etched facet technology in monolithic integration will aid the complexity of polarization and wavelength control.

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[1] See Binoptics proposal for this work. October 2003.